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Scientific and Technical Intelligence Report

Soviet Millimeter Wave Technology and Systems Applications

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September 1976

Soviet Millimeter Wave Technology and Systems Applications

Project Officer

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PRÉCIS

The Soviets may have had deployed for several years a number of military radar and communications systems operating in the [redacted] millimeter wave band. [redacted]

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SOVIET MILLIMETER WAVE TECHNOLOGY AND SYSTEMS APPLICATIONS

Project Officer

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SI 76-10024
September 1976

CENTRAL INTELLIGENCE AGENCY
DIRECTORATE OF SCIENCE AND TECHNOLOGY
OFFICE OF SCIENTIFIC INTELLIGENCE

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PREFACE

This report examines Soviet millimeter wave (30 to 300 GHz) component technology and trends in the application of this technology in military systems. Despite some disadvantages, several features of radar and communications systems operating at these frequencies make them attractive in applications where small size, covertness, and high data rates are considerations.

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TECHNICAL FOREWORD

Millimeter waves, the frequencies between 30 and 300 GHz, are of interest because of the large bandwidths available and the possibility of designing transmitters and receivers in small packages. Large bandwidth means that a radar can have good range resolution or that a communication system can handle high data rates. In addition, there is less likelihood of interference among systems operating in the millimeter wave band because of sparse utilization of the band. Small package size allows the use of a radar, communication equipment, or radiometer in systems where space or weight is at a premium.

Balancing these advantages are a number of technological problems which restrict operation of receivers and transmitters in this frequency band. Transmitter power generally decreases with increasing frequency because the smaller dimensions and closer spacing cause electrical breakdown problems. Receiver sensitivity also worsens and components are difficult and costly to fabricate because of their small size.

Another limitation of systems operating at frequencies above 30 GHz is the severe attenuation introduced by propagation through rain and atmospheric gases. The atmospheric attenuation is not uniform with frequency. "Windows" exist where the attenuation is lower than at adjacent frequencies. One such window centered at 34 GHz is approximately 7 GHz wide; another window centered at 94 GHz is about 23 GHz wide and represents the next logical millimeter wave frequency band for systems which must operate in the atmosphere. If one operates outside the atmosphere, attenuation is not a problem. In fact, radars or communications systems for use in space probably would operate at about 60 GHz. At this frequency the oxygen absorption line in the atmosphere causes severe attenuation and makes the interception of emissions by hostile ground-based Sigint units unlikely.

In addition to radar and communications systems, radiometers (detectors of thermally generated electromagnetic radiation) have certain advantages when operated at frequencies above 30 GHz. In general a radiometer produces an output voltage which is a function (usually linear) of the difference between the target temperature sensed by the antenna and that of a reference. A radiometer is thus capable of passively detecting and perhaps tracking targets such as aircraft, ships, and satellites which have apparent temperatures that differ from those of their backgrounds. This antenna temperature contrast not only is a function of the target-to-background temperature ratio but also depends on the fraction of the antenna beam subtended by the target. Radiometer operation at millimeter wavelengths permits higher resolution ground maps for accurate navigation fixes. This advantage, however, must be weighed against the attenuation due to atmospheric absorption and scattering, which has the effect of blurring the contrast available at the target site.

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SOVIET MILLIMETER WAVE TECHNOLOGY AND SYSTEMS APPLICATIONS

PROBLEM

To assess Soviet millimeter wave technology and determine to what extent it is being applied to military systems.

SUMMARY AND CONCLUSIONS

Before 1972 the USSR had developed and deployed military equipment operating in the millimeter wave band, [redacted] 25X1 25X1

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During the 1960s the Soviets developed an excellent millimeter wave technology base in the 30- to 40-GHz region. This base, which was adequate to support all the applications listed above, was apparently achieved by scaling up in frequency the existing Soviet microwave components, such as magnetrons and waveguides, which operate below 18 GHz. Some of this Soviet technology, such as the capability to build 9-meter parabolic reflector antennas which operate up to 300 GHz, is well ahead of US state of the art.

In addition to a well developed technology base, the Soviets have had considerable experience in nonmilitary millimeter wave systems. This experience strengthens their ability to build military hardware operating above 30 GHz. [redacted] 25X1 25X1

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TRENDS

The Soviets probably will expand their use of the 30- to 37.5-GHz region of the electromagnetic spectrum. In their recent millimeter wave R&D, the Soviets are attempting to develop component technologies unique to the millimeter wave band rather than simply to scale up the frequency of microwave components. Soviet approaches to building low-noise receivers appear promising: Soviet Schottky barrier gallium arsenide diodes and parametric amplifiers are reported to have noise figures which are at least comparable with those of similar US devices and are adequate for use in radar or communications receivers in the 30- to 100-GHz frequency range. In some of their more unconventional approaches, such as their work on the beam plasma amplifier, the Orotron, and the cyclotron resonance amplifier, the Soviets have had only limited success but, nevertheless, appear willing to put extensive effort into solving the problem of high-power generation at millimeter frequencies.

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DISCUSSION

SOVIET MILLIMETER WAVE TECHNOLOGY

Waveguide Technology

For radar application, where waveguides are short and losses are not the major problem that they are in waveguide communications, the Soviets appeared in the past to have relied on scaled-down versions of lower frequency, hollow metal waveguides. These scaled-down waveguides, however, are capable of handling less power than lower frequency guides because air breakdown occurs at lower power levels in smaller waveguides. For example, an air-filled waveguide designed for 35-GHz operation breaks down at about 25-kW peak power; one designed for 94-GHz operation breaks down at 4-kW peak power. The smaller waveguides are also more difficult to manufacture and require more precision tooling. These problems undoubtedly led the Soviets to search for new waveguide designs capable of handling higher power. There is no evidence that they have made a major advance in this area. Where additional power is needed in a radar application, they probably resort to technologies such as pressurized waveguides filled with sulfur hexafluoride or multiple-waveguide feeds to provide some increase in radar peak power capability.[1]

While the Soviets are not known to have solved the high power handling problem, they have developed an excellent capability to produce specialized millimeter waveguides having low propagation losses. The types of waveguides developed include (1) dielectric lined, (2) helical, (3) multimode oversize, (4) corrugated, and (5) beam mode. According to the Soviets, the first four types were investigated primarily for their application to waveguide communication systems. The beam mode waveguide is a quasi-optical transmission line having particular application above 100 GHz, where the dimensions of a dominant mode rectangular guide become so small that fabrication is difficult.[2]

The development of millimeter waveguides for communications systems was begun in the 1950s at the direction of the Ministry of Communications.[3–8] The Institute of Radio Engineering and Electronics (IREE), Moscow, has been the principal developer and has remained involved to the present. Its primary input now is the solution of theoretical problems and preliminary design of terminal apparatus, regenerative amplifiers, and new test equipment.

The Soviets claim that the waveguide which they have developed and are testing for buried communication systems has losses of 2.7 to 3.5 dB/km. It consists of all metal waveguide sections with helical waveguide sections placed periodically every 50 to 60 m. The helical waveguide sections damp undesirable modes arising from mode conversion and have a damping factor of about 1 dB/m.[9] [10] These performance figures compare favorably with those of

similar waveguides developed in the United States and other countries. In addition, Soviet researchers have described a polyethylene dielectric millimeter waveguide, which they claim to be inexpensive and suitable for wide-band communications systems.[11]

The Moscow Power Engineering Institute has also been active in millimeter waveguide development. Their contribution has been in the areas of solid dielectric waveguides, rotating ring junctions, and multiarm assemblies for coupling.[12–18] These devices are applicable to a wide range of systems and could be used in the design of a variety of radars. Institute researchers stated that they have developed resonators, loads, attenuators, phase shifters, and frequency selection devices that are compatible with the dielectric waveguide. Their early work with dielectric waveguides also included antenna design. One such design used a number of dielectric rods to form the radiator; the antenna pattern was in turn formed by adjusting the electrical length of each rod.[19]

Detectors

Soviet progress in the development of millimeter wave detectors has followed a pattern similar to that of the United States. The earliest operational (1959) Soviet detectors were used in radiometers devoted principally to radio astronomy. These radiometers used indium antimonide (InSb) detectors that required cryogenic cooling and an external magnetic field. More recently the Soviets have claimed InSb detector sensitivity of 2×10^{-12} W for a 1-cycle bandwidth in the 2- to 4-mm band.[20–23] The date of this information is the late 1960s, making the Soviet parameters slightly better than the results reported by United States researchers at the time. The cooling hardware required by this detector makes it unattractive for military applications. Another disadvantage is that direct detection devices such as InSb detectors are not as sensitive as superheterodyne receivers.

Development of GaAs devices, both epitaxial and nonepitaxial, operating in the high-field domain (Gunn) and limited space-charge accumulation (LSA) modes was the next major Soviet step in millimeter wave detector technology. Little information is available on specific Soviet device fabrication techniques although they are thought to resemble closely those which the Soviets employ in producing light emitting diode structures.[24 25]

The Soviets reported in 1970 Schottky barrier GaAs diodes having a barrier capacitance of 0.07 picofarad and a series resistance of 4 ohms. These figures result in cutoff frequencies of about 700 GHz. Theoretical conversion losses can be determined as a function of the pulse-duty cycle and the ratio of operating to cutoff frequency; allowance must also be made for degradation due to waveguide mount efficiency. Assuming waveguide mount losses comparable with US devices and a cutoff frequency of 700 GHz, conversion losses of 7 to 9 dB over the frequency range 30 to 100 GHz could be expected from the Soviet device. These losses are quite low for 1970, and the Soviets presumably have continued to reduce the noise levels.[26–30] If the described GaAs Schottky barrier diode were coupled to low noise amplifiers, the Soviets might be capable of building radar or communications receivers with noise figures of 14 to 16 dB. In contrast with this possible level of performance, the Soviet "OLP" airfield traffic control radar has a receiver noise figure of 23 dB at 37.5 GHz. The OLP receiver probably used an older tube technology. A more recent example of Soviet technology is the receiver section of the regenerative repeaters which the Soviets built for their Moscow waveguide system and for a possible line-of-sight millimeter wave communications system. Here the Soviets achieved a noise figure of 18 dB with an intermediate frequency passband of over 300 MHz at 35 GHz.[31]

A large Soviet effort to develop millimeter wavelength parametric amplifiers is under way and most of the indicated applications are radiometer front ends. These amplifiers, however, are also usable in low-noise, high-resolution radar and high data rate communications systems. Data from 1967 to 1971 indicate development in the 30- to 40-GHz range, with some preliminary developments at 70 to 90 GHz. An 8-mm parametric amplifier report in 1970 had a noise temperature of 550° K, 16 dB gain, and a bandwidth of 200 MHz.[22 32] In 1973 an 8-mm parametric amplifier was reported with a noise temperature of 300° K, 13 dB gain, and a bandwidth of 1 GHz.[33] The improvements were due to improved diodes and lower circulator losses. If such a rate of improvement continued, it would result in parametric amplifier performance figures of about 150° K noise temperature and 1-GHz bandwidth at 35-GHz by 1976. The specific parametric amplifiers mentioned were all uncooled devices with sufficient package development for use in operational systems. Overall,

by 1976 the Soviets should now have a detector technology, using uncooled parametric amplifiers, suitable for the design of receivers for high sensitivity, high-resolution radars or high data rate communications systems in the 35 GHz range. Soviet Schottky diode technology should permit the design of radar or communications systems operating up to 100 GHz.

Vacuum Tubes

Most Soviet millimeter wave tube designs are based on the conventional designs used in the lower microwave bands, but scaled down in size. The scaling down limits the power handling capabilities of these tubes, however, just as it does in the waveguide case.

The Soviets have published the operating parameters of a family of low-power klystrons, the K 700 series, which operates at 35 to 80 GHz with 20 to 30 mW of output power. These klystrons have very wide bands, with widths ranging from 20% of center frequency at the lower millimeter wave frequencies.[34] The Soviets, however, possess a strong high-power klystron technology base for decimeter frequencies (300 MHz to 3,000 MHz) and probably could also develop high-power millimeter wave klystrons. These would deliver several hundred watts of output power but would require substantial amounts of primary power and possibly special cooling.[35] Klystrons known to be earmarked for the Soviet military in 1965 included a device at 37 GHz. Whether this was a high power (transmitter) or low power (local oscillator) tube is not known. The tube, developed at Scientific Research Institute 160 (NII-160), very likely went into a Soviet military system several years ago.[36]

The Soviets have also developed a family of backward wave oscillators (BWOs) which operate in the 35- to 80-GHz region.[33] Again the only reported devices are of low power, 0.5 W, with gains of about 10 dB. The Soviets, however, possess an excellent BWO technology base, as manifested in their carcinotron development programs. Soviet carcinotrons operate from 100 to 1,500 GHz, with a few milliwatts of output power. The technology employed should allow production of efficient BWOs at millimeter wavelengths capable of delivering several watts of output power. Such BWOs probably would be unsuitable for radar but might have communications application.

The tubes described above represent conventional approaches to power source design. Because these tubes are difficult to push to higher powers, the Soviets apparently are pursuing a number of R&D efforts in unconventional tube design, probably in an attempt to find a suitable high power generator for radar applications. The Soviets are not expected to publicize any successful efforts in this regard. Some of their well publicized, but so far apparently unsuccessful, efforts are discussed below.

The Soviets have been particularly active in the field of beam plasma amplifiers (BPAs). These devices employ a hot gaseous plasma as the frequency determining element and theoretically are not subject to the power limitations that prevail for microwave tubes having metallic resonant structures. Most of the Soviet effort has been conducted at the Institute of Radioengineering and Electronics (IREE) under the direction of Zarim Chernov, although plasma theorists from an atomic energy plasma research group at Kharkov have also contributed to the effort. In 1961 the IREE reported gains of 30 to 40 dB at 38 GHz, but the accompanying noise levels were quite high, 24 to 38 dB. By 1965 BPA test devices were being produced at 8 mm and 2 mm. A year later, noise levels as low as 15 dB were reported and several kilowatts of power were achieved at wavelengths as long as 10 cm. Subsequently, the Soviets achieved a 100-W output at 38 GHz.[35] The Soviets believe that the high noise and

difficult coupling methods of BPAs are not fundamentally limiting and that BPAs offer substantial potential as a power source at the shorter millimeter wavelengths. This belief stands in contrast to US programs, which have devoted little effort to BPAs in recent years and indicates a Soviet willingness to pursue unorthodox and often difficult approaches to power generation. The Soviet program probably is continuing in part because of the applicability of the technology as a heating mechanism for controlled thermonuclear research.

The cyclotron resonance amplifier functions by means of the interaction between a spiraling high-velocity electron beam and an induced longitudinal magnetic field. Power gain is produced at approximately the electron gyrofrequency. Considerable theoretical work has been undertaken in both the Soviet Union and in the United States on this phenomenon. In 1968 the Soviets may have reached a more advanced hardware stage with a device that produced 1-kW CW power at a claimed efficiency of 25% at 38 GHz; the amplifier bandwidth was about 300 MHz. This early device work has reportedly led to the development of amplifiers that produce several kilowatts of power in the upper part of the millimeter wave band.[37] The Soviets have reported 12-kW continuous output power at 107 GHz with a cyclotron resonance amplifier. At 140 GHz they reported 2.4-kW continuous power and 7.0-kW pulsed power output. These claimed power levels are some of the highest yet produced at these frequencies but the device appears unsuitable for radar applications. The Soviet cyclotron resonance amplifier research is also significant because of its use of cryogenic techniques. To generate the intense magnetic fields needed to operate at millimeter wavelengths, the Soviets have used superconducting solenoids.[38–39]

Another unique Soviet development, the Orotron, employs an open resonator and represents an extension of optical techniques to the millimeter wave range. Currently these Soviet devices are capable of only relatively low power, 4 W with a beam current of 1 A. The Soviets are continuing to work in this area with the hope that higher power levels might be attained.[36]

Solid State Sources

The Soviets in 1967 were primarily interested in impact avalanche transit time (IMPATT) diodes. During the last 5 years a large increase has also been noted in the number of Soviet reports dealing with the Gunn effect in GaAs bulk material. Acutal performance figures are quite limited. Projections can nonetheless be made based on the large number of theoretical papers published in the seventies, the availability of good quality GaAs to researchers at both military and Academy of Sciences related institutes, and the increased Soviet interest in millimeter wave systems.[40–46] The figures in table 1 are estimates of power output and their absolute accuracy cannot be guaranteed. The absolute accuracy, however, is not as important as the fact that even with devices having poorer power performance than those of table 1, the Soviets could still use these devices in the design of workable radar and communications systems. From the single viewpoint of power generation, the performance figures of table 1 parallel closely those obtained by US researchers. However, the ultimate utility of this device capability to the Soviets will also involve their ability to stabilize the temperature and frequency of these devices and in certain applications tune them through a frequency band.

A promising future development in millimeter wave technology is the millimeter wave integrated circuit. The Institute of Radio Engineering and Electronics (IREE) has attempted to provide transmission lines for millimeter wave integrated circuits, a field in which little Soviet activity has been reported. One specific Soviet design consists of a high permittivity dielectric bar placed on a grid of metal backing. The performance characteristics of the transmission line have not been mentioned, but it is likely that this configuration would suffer from very small air gaps between the dielectric and the conducting ground plane. These air gaps are difficult to eliminate and make circuit performance unpredictable. A US

Table 1

Current Estimates of Soviet Solid-State Source Capability

Type of Diode	35 GHz	70 GHz	94 GHz
Gunn Diodes (high-field domain—CW).	100 mW	50 mW	15 mW
Impatt Diodes (CW)	1 W	500 mW	250 mW
Gunn Diodes (LSA—pulsed)	3 W	700 mW	400 mW

solution to this problem is to isolate the high permittivity bar from the conducting ground plane with a thin layer of polyethylene. Other possible Soviet difficulties with millimeter wave integrated circuits (ICs) would be lack of adequate computer-aided design programs and inadequate modeling of active devices, especially at high power. These deficiencies are difficult for the Soviets to correct and probably will require several years of effort. While Soviet progress in millimeter wave ICs is expected to be slow, any success in this area would be significant because it could lead to the development of inexpensive, very small radars and communication systems.

Antennas

The Soviets have an excellent capability for building large millimeter wave antennas. The area in which the Soviets are most active has been in the development of radiotelescopes utilizing moderate size reflectors (7 to 10 m), which are capable of operating up to 300 GHz. This effort began in the late 1950s with the RT-22 radiotelescope, which operates at 10 and 37 GHz. In the mid-1960s the Soviets developed a technique of compensating for the deformation of the main dish by subdividing the main reflector and subreflector into sections which were automatically positioned by an electronic control system to maximize the antenna's performance. This technique yielded favorable results but was costly to implement and subsequently the Soviets began to develop structural methods of compensating for the deformation of the main reflector. The most promising consists of constructing the panel support structure so that, as the dish deforms, its shape remains parabolic but with a different focal length. The feed is then displaced to compensate for this change in focal length.[47]

The Soviets have also developed the necessary techniques for controlling the surface tolerance of dish antennas to allow them to operate up to 300 GHz. They appear to have the capability to control the surface of a 9.2-m reflector to better than 0.1 mm. This is comparable with or better than that achieved in the United States. These surface tolerances can be maintained during tracking. Such maintenance is very significant, not only for the radio astronomy application but also for radar applications. Some of the Soviets who developed these large millimeter wave antennas are reported to be working at the Moscow Scientific Research Institute for Instrument Building (MNIIPS, formerly NII-17 of the Ministry of Aviation Industry), which is believed to be responsible for ABM and satellite-borne radar design.[47, 48] 25X1

SOVIET MILLIMETER WAVE SYSTEM TRENDS

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Several military uses of the millimeter wave frequency band have been made feasible for the Soviets by development of their technology base. Some of these uses are discussed below.

Radiometers

Radiometers operating at frequencies above 30 GHz may be of interest to the Soviets for battlefield surveillance, target location, or terminal homing application. The radiometer's great advantage is that it is a passive sensor and, therefore, not identifiable through Elint.

Overall Soviet capability in radiometer technology is about on a par with that of the United States. Soviet technology is adequate for the design of radiometers for all the applications listed in the preceding paragraph. The best Soviet radiometer capability is represented by superheterodyne radiometers of the Dicke type. This radiometer uses a modulator to view alternately a reference load (at a known temperature) and the antenna. The Soviets have both switched ferrite circulators and tuning-fork-controlled mechanical modulators for such radiometers.[51–55] The critical component in such a radiometer is the mixer, whose noise level determines the radiometer sensitivity. As previously mentioned, the Soviets have the capability of building low conversion loss mixers using Schottky barrier diodes.

An analysis has been performed to determine radiometer sensitivities (measured in noise-equivalent temperature differences—NETDs) based on Soviet component capability. The results, summarized in table 2, are based on an output signal-to-noise voltage ratio of unity, which is the usual method of specifying radiometer sensitivities. The estimated Soviet capability as shown in table 2 is quite good and parallels that achievable in the United States. In actual quantitative measurements, however, a signal-to-noise ratio of as much as 10 dB may be required. This increases the temperature difference necessary for accurate tracking by that amount. For example, if one wished to use the 35 GHz radiometer with a 1-second integration and a 10-dB signal-to-noise voltage ratio to track a target, the target would have to produce at least a 3° K difference temperature at the antenna terminal.

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Table 2

Soviet Radiometer Sensitivities

	35 GHz		94 GHz	
	Soviet	US	Soviet	US
L_{RF}	1.5 dB		d dB	
L_C	7.5 dB		8.5 dB	
F (double channel)	11.9 dB		14.5 dB	
B_{IF}	1 GHz		1 GHz	
NETD (γ=0.1 s)	0.9°K	0.7°K	1.6°K	1.3°K
NETD (γ=1 s)	0.3°K	0.23°K	0.5°K	0.4°K
NETD (γ=10s)	0.09°K	0.07°K	0.16°K	0.13°K

L_{RF}—Radio frequency losses preceding mixer.
L_C—Mixer conversion loss.
F—Radiometric noise figure.
B_{IF}—Intermediate frequency bandwidth.
NETD—Noise equivalent temperature difference.

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APPENDIX

Design Parameters of Soviet Millimeter Radar Systems

Radar systems are evaluated by examining the radar range equation for a given set of component performance figures and target characteristics. The range equation, which is applicable at all wavelengths, is given by:

$$R^4_{max} = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 K T_o F_n (S/N) B_{eff}} \cdot \exp(-2\alpha R_{max}) \quad (1)$$

where

R_{max} = maximum range, m

G = antenna gain

λ = wavelength

σ = target cross section, m^2

k = Boltzmann's constant, $1.38 \cdot 10^{-23}$ T/°K

T_o = 290°K

F_n = receiver noise figure

S/N = signal-to-noise ratio required for detection

B_{eff} = effective noise bandwidth

α = atmospheric attenuation constant

P_T = transmitter power, w.

The receiver noise figure, F_n, and the effective noise bandwidth, B_{eff}, depend on the system configuration and the mode of operation of the radar system:

$$F_n = L_{RF} L_c \quad (NR + F_{TF} - 1)$$

where

L_{RF} = the receiver RF circuit losses

L_c = mixer conversion loss

NR = crystal noise ratio

F_{IF} = total IF noise figure,

and

$$B_{eff} = \frac{B_n}{{}_n E_I(n)}$$

where

B_n = noise bandwidth

n = number of bits integrated

$E_I(n)$ = integration efficiency.

The noise bandwidth, B_n, has a range of possible values depending entirely on the mode of operation. In an FM-CW mode of operation, B_n can be small ($<10^3$ Hz) and this is desirable for operation at long ranges. However, when high powered pulsed sources are used, B_n must be large ($<10^6$ Hz) to accommodate the spectrum of very narrow pulses.

Equation (1) has been solved for a number of generalized cases. These data are presented as a set of curves with range plotted versus the product of peak transmitted power times the square of the antenna gain ($P_T G^2$), as it appears in the numerator of equation (1). The computations were performed for the 35-GHz and 94-GHz atmospheric windows, for several values of B_{eff}, and for atmospheric conditions ranging from free space to a moderately heavy (4 mm/h) rainfall. The results of these computations are given in figures 4 through 11. The computations have been extended over a sufficiently large range to allow one to upgrade the predicted system performance based on any new intelligence indicating an improvement in component capability.

The range decreases shown for the various rainfall rates are pessimistic in that they assume the total loss over the entire propagation path. A 4-mm/h rain is quite severe and anything greater than this would in most cases occur in the form of a local squall and hence contribute loss over some fraction of the total propagation path. This would extend the ranges given in these calculations.

The receiver noise figures used for the range calculations are representative Soviet state of the art. The choice of antenna gain is determined not only by range considerations but also by possible volume and weight constraints. Values of $P_T G^2$ have been extended to include the highest power Soviet magnetrons coupled to 80-dB gain antennas.

All computations have been performed for a target cross section of one square meter. This amounts to a transfer function which allows one to go from the power density in a plane containing the target to the

power delivered per unit solid angle in the direction of the receiving antenna. Two important distinctions arise at millimeter wavelengths. When the targets of interest are many wavelengths in extent in both transverse directions, their cross section is essentially frequency independent (neglecting fine structure). In these cases the radar back scattering cross section increases with decreasing wavelength. Hence, certain targets may be electrically larger at millimeter wavelengths. Examples of this type of target are objects composed of aggregrates of small members such as bridges and towers. Hence, for this class of targets, the range reduction due to atmospheric losses when going up in frequency can be substantially offset by their increased scattering cross section.

All of the above considerations, and the use of reported Soviet component performance figures, ensure that the range calculations of figure 4 through 11 are presently realizable. Systems operating in the atmosphere (as opposed to satellite systems) have curves which tend to flatten at the longer ranges due to higher dissipation along the propagation path. Hence, considerable variation in individual component performance is necessary to change the maximum range appreciably.

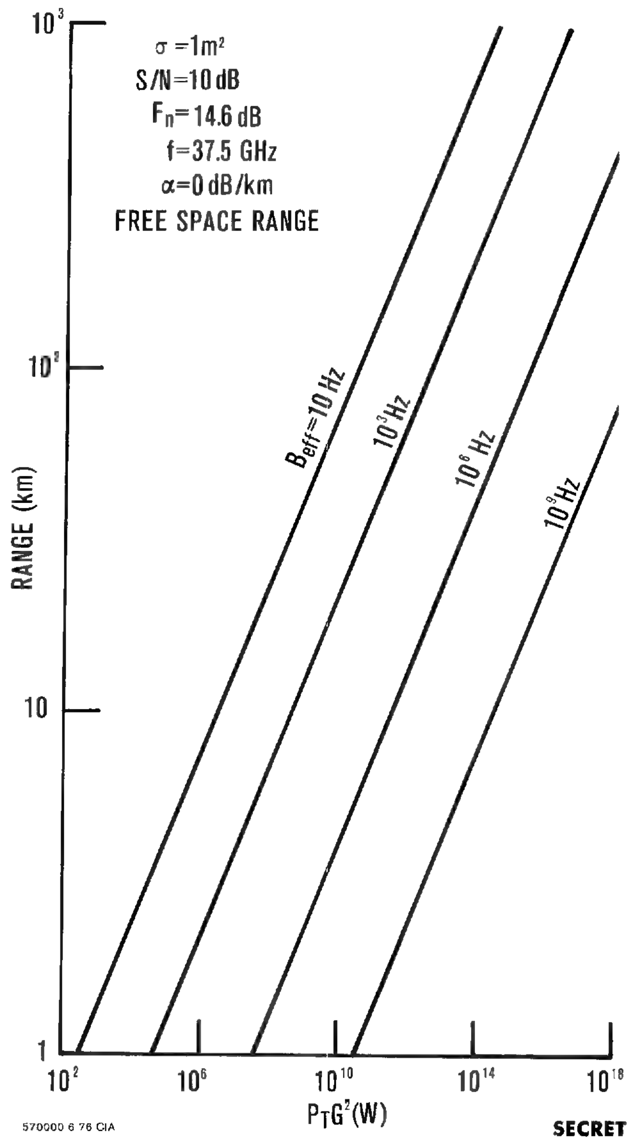

Figure 4. Radar Range in Free Space at 37.5 GHz

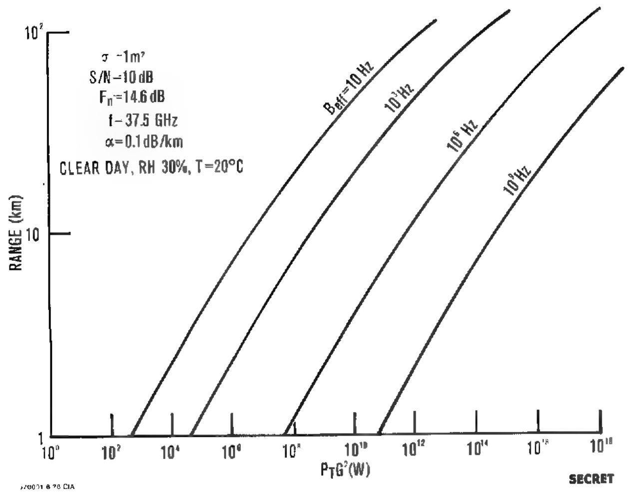

Figure 5. Radar Range in the Clear Atmosphere at 37.5 GHz

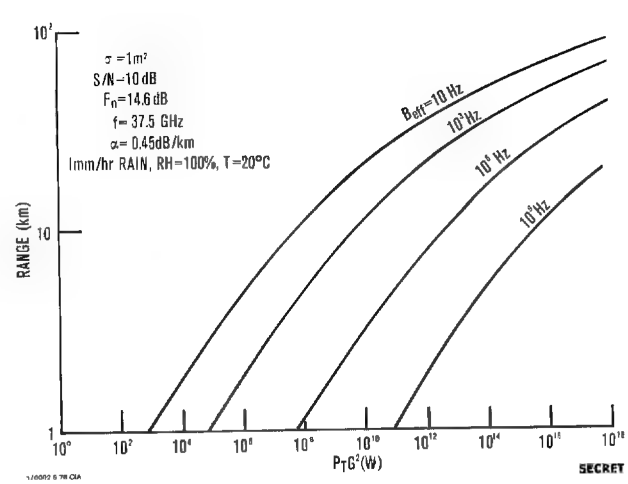

Figure 6. Radar Range in 1 mm/h Rain at 37.5 GHz

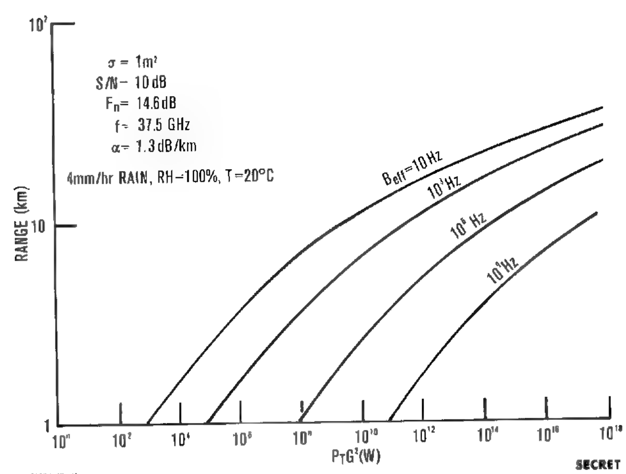

Figure 7. Radar Range in 4 mm/h Rain at 37.5 GHz

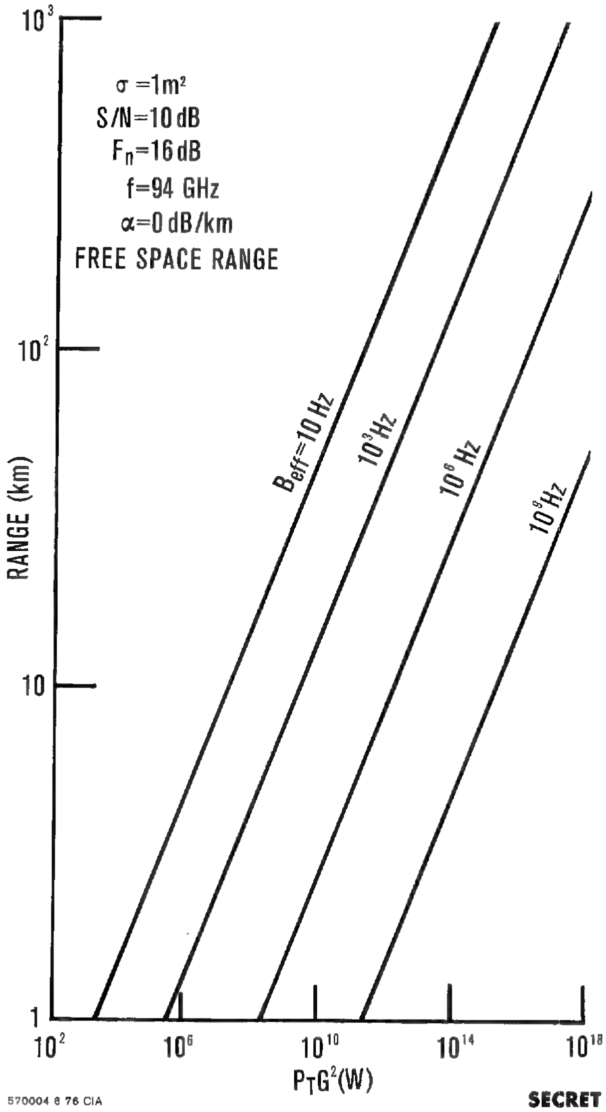

Figure 8. Radar Range in Free Space at 94 GHz

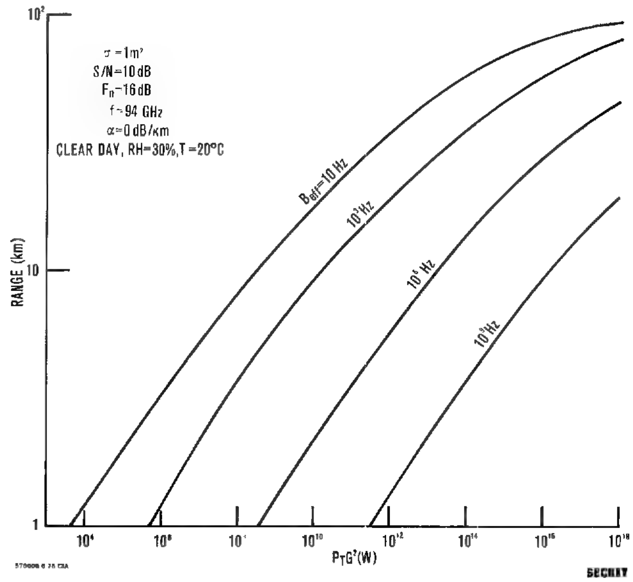

Figure 9. Radar Range in the Clear Atmosphere at 94 GHz

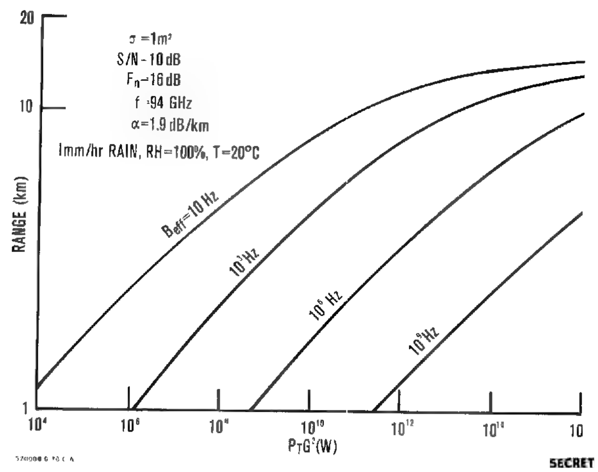

Figure 10. Radar Range in 1 mm/h Rain at 94 GHz

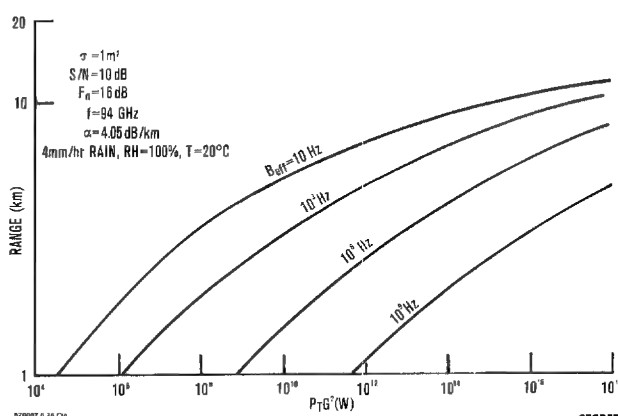

Figure 11. Radar Range in 4 mm/h Rain at 94 GHz

Radio Science, Volume 11, Number 11, pages 915-920, November 1976

A technique for simultaneous measurement of attenuation and bistatic scatter due to rainfall at millimeter waves

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A shuttle-pulse technique for simultaneous measurement of the attenuation and bistatic scatter of millimeter waves is described. Measurements were obtained using a propagation path through rain of only a few meters; therefore, the rainfall statistics can be considered constant within the sample volume. Absorption data resulting from this experiment show a disagreement with theory similar to that previously reported. A "total bistatic scatter coefficient" for rain is defined, and the technique of using a shuttle pulse for its measurement is discussed.

INTRODUCTION

A technique for simultaneous measurement of the attenuation and bistatic scatter of millimeter waves resulting from rainfall over short path lengths is described in this paper. Measurements were made with a shuttle-pulse technique which utilizes a propagation path through rain of only a few meters. Absorption data [*Medhurst*, 1965; *Godard*, 1970; *Mink*, 1973] obtained from measurements over relatively long transmission paths are in some disagreement with theoretical expectations. Results of this experiment for very short path lengths show a similar disagreement which indicates that the discrepancy between theory and experiment cannot be explained in terms of variations in the rainfall-rate and drop-size distribution along the path.

The total bistatic scatter coefficient per unit length defines an equivalent scatter area for all drops within the millimeter wave beam. From this quantity, the scattered-signal level caused by rainfall may be determined.

The experimental setup used for the reported measurements is shown in Figure 1. A short millimeter wave pulse (35 GHz) is injected into a wave beam resonator, where it shuttles back and forth between the two spherically shaped reflectors. After many round trips, if the resonator is properly designed, a gaussian beam mode is established whose amplitude decays exponentially [*Christian and Goubau*, 1961]. When part of the path is intercepted by rain, the resulting increase in pulse attenuation per round trip is a measure of the rain attenuation. The bistatic scatter coefficient for rain can also be measured with this shuttle-pulse technique by placing a second receiving system at the desired scatter angle. The system is calibrated by placing a known scattering object in the beam.

DESIGN OF WAVE BEAM RESONATOR

The reflectors of the resonator have a diameter of 1 m and a focal length of 28 m; their mutual spacing is 25 m. At the center of each reflector, there is a 1 × 1 cm coupling aperture which is used to inject and withdraw the vertically polarized millimeter wave signal. The 35 GHz magnetron, which was used as the signal source, supplies 70 ns pulses with a peak power of 10 kW. The measured loss of the cavity without rain is 0.1 db per round trip; the theoretical diffraction and reflection loss of the reflectors is 0.048 db per round trip [*Goubau*, 1968]. The additional loss of 0.052 db is caused primarily by the coupling apertures.

MEASUREMENTS OF ATTENUATION CAUSED BY RAIN

The receiving system is a conventional crystal detector followed by a wideband video amplifier; the signal processing system, which compensates for power variations of the magnetron, follows the video amplifier. After the gaussian mode has been established (see Figure 2), the pulse train is gated (using an FET switch) into an integrator circuit starting at time t_1. This pulse train is also gated into a second integrator circuit, which starts at a

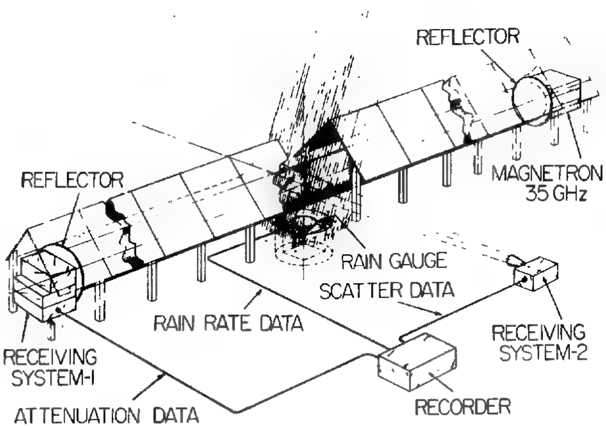

Fig. 1. Overall view of measuring system.

later time, t_2. The ratio between the outputs of these two circuits is then formed and the resulting curves plotted by a strip chart recorder. This ratio is a function of the attenuation factor of the pulse train since the difference between the two switching times is constant. Calibration of the system is accomplished with an oscilloscope by measuring the decay of the pulse train for various losses.

Since this measuring technique requires a path length through rain of only 5 m or less, the remaining part of the beam path between the reflectors is covered by a roof. Only one rain gauge is required for measuring the precipitation rate within this short path. In order to obtain rain data at sufficiently short intervals, a special tipping bucket gauge was constructed [*Mink and Forrest*, 1974]. This gauge tips after each 5×10^{-3} mm of rainfall has collected; each bucket tip is recorded as a hack mark on the strip chart recording.

The data obtained during these experiments were evaluated in accordance with the empirical relation between attenuation and rainfall as proposed by *Gunn and East* [1954]:

$$L = AR^x \qquad (1)$$

where L is the attenuation per kilometer and R is the rainfall rate in millimeters per hour. The parameters A and x were obtained by fitting the curve represented by equation (1) to the measured points with minimum square error. In order to obtain the most reliable data points, the measurements were evaluated for periods of relatively constant rain, i.e., constant attenuation. Data were taken for an average of 50 min during each shower. These data are represented by the dots in Figure 3; the best fit curve to these data is shown in the form of a dashed line. For comparison, the theoretical attenuation results of *Medhurst* [1965] are plotted in the form of a solid line.

On the basis of the above data, which were obtained from measurements of rainfall samples of uniform rate, one must conclude that there is no well-defined relationship between rainfall rate and millimeter wave absorption. This indicates that the rain statistics (i.e., drop-size distribution, index of refraction, and terminal velocity) for a certain rainfall rate vary substantially.

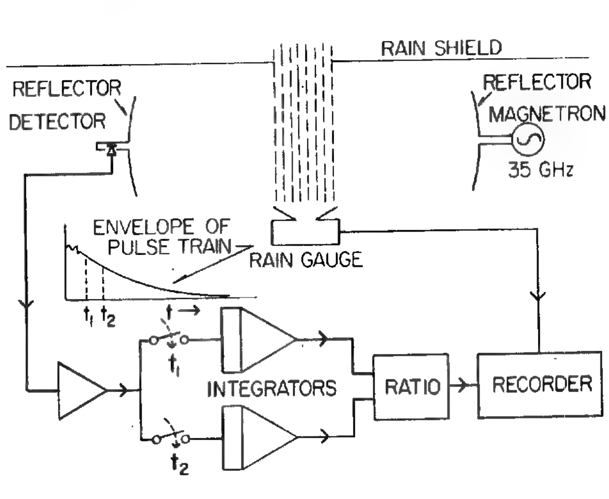

Fig. 2. Rain-attenuation measuring system.

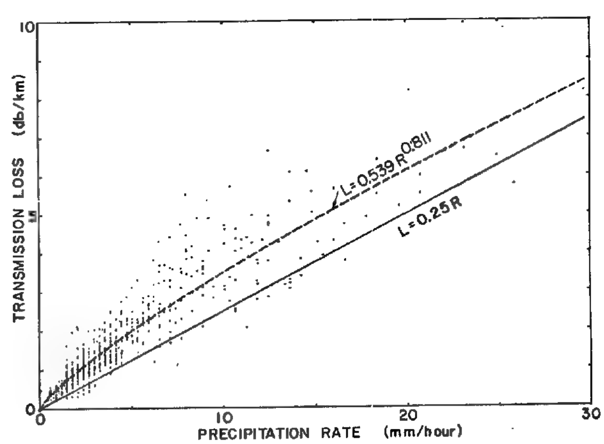

Fig. 3. Comparison of experimental and theoretical rain attenuation data.

MEASUREMENTS OF SIDE SCATTER CAUSED BY RAIN

Since communication systems are being planned to operate in the millimeter wave length bands, a knowledge of the side-scatter (bistatic) characteristics of millimeter waves caused by rainfall becomes important. One vital aspect of bistatic scatter caused by rain, and a reason for this study, is that of security. If sufficient energy is scattered by rain, the security of a millimeter wave relay system can be compromised by placing a receiver alongside the path. Cross coupling between millimeter wave links is also a serious problem. Satellite systems are particularly subject to cross-coupling interference. In this section, the "total scatter coefficient" for rain is defined, and the shuttle-pulse technique used during this investigation for its measurement is discussed.

The received power scattered by a single drop as given by *Cleverley* [1973] is

$$P_r = \mathscr{P}_{(r)} (\sigma_x / 4\pi d_r^2) A \tag{2}$$

where

$\mathscr{P}_{(r)}$ = $|\bar{E} \times \bar{H}|$ at the drop,
σ_x = bistatic-scattering cross-sectional area of the drop,
d_r = distance from the drop to the receiver,
A = the area of the receiving aperture

For calculation of the overall effect of raindrops on a gaussian beam, a density function for rainfall is defined as follows [*Kerr*, 1951]:

$$N_v = \int_{\text{vol}} n \, dv \tag{3}$$

where n is the number of drops per cubic meter, and N_v is the total number of drops within the scattering volume. Since the drops have a random distribution within the scattering volume, the scattered power from each drop [*Kerr*, 1951] must be added. The total received power then becomes:

$$P_T = \frac{A}{4\pi} \int_{\text{vol}} \frac{n \mathscr{P}_{(r)} \sigma_x}{d_r^2} dv \tag{4}$$

Since evaluation of equation (4) is in general rather difficult, the following approximations will be used. The scatter volume is considered to be cylindrical in shape with its axis along the axis of the millimeter wave beam. This scatter volume is considered to be relatively small and far enough away from the receiver so that σ_x and d_r can be considered constant. Using these approximations, equation (4) when normalized per unit length becomes:

$$P_T / L = (A / 4\pi d_r^2) \, SP \tag{5}$$

where the total power incident upon the common scatter volume is

$$P = \int_{\substack{\text{incident}\\ \text{beam}\\ \text{area}}} \mathscr{P}_{(r)} \, dr \tag{6}$$

If one assumes that the path length through the common scattering volume is short enough so that attenuation may be neglected, the total side-scatter coefficient per unit length is

$$S = n\sigma_x \tag{7}$$

Thus, if S is determined by measurements such as those described below, the side-scatter signal level may be determined. Of course, one must take into account the attenuation of the signal and the angular sensitivity of the receiver when determining the total received side-scatter signal for a long propagation path through the common scatter volume.

The experimental setup used for the rain side-scatter measurements is shown in Figure 4. Since the resonator setup and the magnetron with its modulator are the same as previously described, only the equipment used for side-scatter measure-

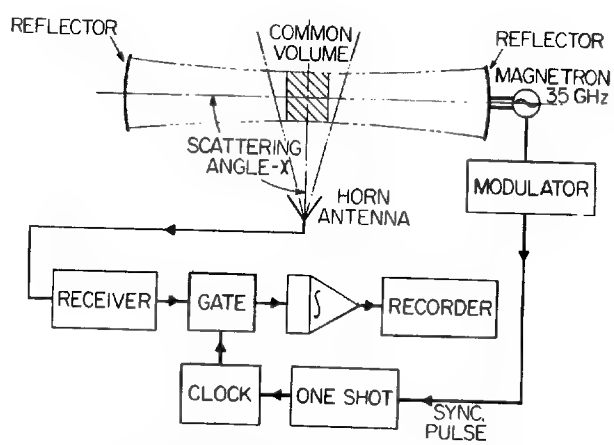

Fig. 4. Rain side-scatter measuring system.

ments is discussed here. Each time the shuttle pulse within the resonator passes through the portion of its path that is intercepted by rain, a portion of its energy is scattered. This scattered energy is detected by the side-scatter receiver. Thus for each round trip of the shuttle pulse, the output of the receiver is two pulses, one for each direction of travel of the shuttle pulse.

Side-scattered energy is collected over an aperture of 33 cm^2, placed 12 m from the common scattering volume, and positioned at the desired angle relative to the beam axis. A conventional millimeter wave superheterodyne receiving system was employed for this experiment. The receiver consisted of a balanced mixer, a 120 MHz post amplifier, and a video detector. Automatic frequency control was employed to keep the receiver properly tuned to the magnetron frequency.

Since the receiver gives an output for each passage of the shuttle pulse through the common scatter volume, the receiver output contains information about both the forward- and backward-scattering angles. To eliminate this ambiguity, the output of the receiver is gated with a synchronous gating circuit so that an output is generated only when the shuttle pulse passes through the common scattering volume in one direction. The pulse train thus generated is gated (using an FET switch) after the gaussian mode has been established (see Figure 2) into an integrator circuit. The output of this integrator circuit is plotted by a strip chart recorder. Calibration of the system is accomplished by measuring its response to a known scatter object (i.e., a thin wire) placed in the common scattering volume. The theory of calibration can be found in appendix A.

Results of side-scatter measurements for a single scattering angle are indicated by the circles in Figure 5. For comparison, theoretical points, based on Mie's scatter theory with Laws and Parson's drop distribution, are shown as crosses in Figure 5 [*Vogel*, 1971]. As can be seen from this curve, the "total side-scatter coefficient" increases at a much faster rate than does the attenuation by rain. A similar result has been reported for radar backscatter as compared to attenuation caused by rain [*Brinks*, 1973]. Using the results of the measurements shown in Figure 5 and equation (5) one finds, for a receiving aperture of 33 cm^2 placed 12 m from the common scatter volume in the plane containing the beam axis and the magnetic field,

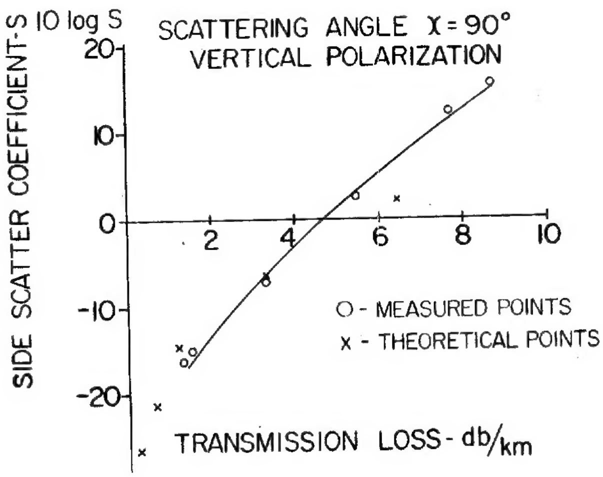

Fig. 5. Measured data for rain side scatter.

that the power received is 60 db below the beam power for a moderate rainfall (~10 mm/hr).

CONCLUSIONS AND RECOMMENDATIONS

A laboratory technique for simultaneously measuring the attenuation and bistatic scatter of millimeter waves has been demonstrated. Since this technique requires a path length through rain of only a few meters, the rain statistics for this path can be considered uniform. Since the quantity of data obtained from each rain event is substantial, it would be desirable to incorporate an automatic data processing unit into the system. This technique would reduce the data to usable form on a real-time basis.

APPENDIX A: THEORY OF SIDE-SCATTER CALIBRATION

In order to calibrate the measuring system, it is necessary to determine the receiving system's response to an arbitrary lossless scattering object placed in the millimeter wave beam.

The power in the shuttle pulse can be represented as a function which decreases exponentially with time. Thus

$$P_{(t)} = P_0 \exp(-2\alpha t) \quad \text{(A1)}$$

where P_0 is the initial power and α is the attenuation factor. If equation (A1) is used with (2), the scattered power as a function of time will be a pulse train whose envelope may be expressed as:

$$P_s/P_0 = (A/4\pi d_r^2)\, S \exp(-2\alpha t) \qquad \text{(A2)}$$

In the signal processing system shown in Figure 4, the pulse train is gated (using an FET switch) into an integrator circuit starting at time t_1 after the gaussian mode has been established, and ending after the pulse train has decayed. The output of the integrator circuit, which is recorded on a strip chart recorder, may be expressed as:

$$\mathscr{F} = \frac{AK(\tau)}{4\pi d_r^2}\int_{t_1}^{\infty} SP_0 \exp(-2\alpha t)\, dt \qquad \text{(A3)}$$

which after integration becomes

$$\frac{\mathscr{F}}{D} = \frac{AK(\tau)}{4\pi d_r^2}\frac{SP_0}{2\alpha}\exp(-2\alpha t_1) \qquad \text{(A4)}$$

where

A = area of the receiving aperture,
$K(\tau)$ = a constant dependent upon the pulse width and spacing between pulses of the pulse train,
d_r = distance from the scattering object to the receiver,
D = path length through rain

When a known scattering object is placed in the millimeter wave beam, equation (A4) becomes:

$$\mathscr{F}_0 = \frac{AK(\tau)}{4\pi d_r^2}\frac{\sigma_0 P_0}{2\alpha_0}\exp(-2\alpha_0 t_1) \qquad \text{(A5)}$$

The resulting signal is then used as the reference level for measurements of side scatter due to rain. When using the same receiving aperture A and distance d_r for both calibration and measurement purposes, one obtains the ratio between equation (A4) and (A5). Thus

$$\frac{\mathscr{F}}{D\mathscr{F}_0} = \frac{S\alpha_0}{\sigma_0 \alpha}\exp[-2(\alpha - \alpha_0)t_1] \qquad \text{(A6)}$$

where $\mathscr{F}/D\mathscr{F}_0$, α, and α_0 are obtained from measurements of the received side-scatter energy and the attenuation of the millimeter wave beam. A more convenient form of equation (A6) for evaluation purposes is:

$$10 \log S = 10 \log (\mathscr{F}/D_0) + 10 \log \sigma_0 + 10 \log(\alpha/\alpha_0) + 8.68(\alpha - \alpha_0)t_1 \qquad \text{(A7)}$$

When equation (A7) is used to determine S, all parameters are known through measurements except σ_0. We will now show how σ_0 can be obtained for a known scattering object such as a lossless wire. A thin wire was chosen for two reasons: (1) its scatter characteristics can be obtained analytically, and (2) in the case of a vertical wire, no supporting structures intercept the millimeter wave beam.

For a thin wire, long in terms of wavelengths, the current is filamentary and its distribution is proportional to the electric field intensity parallel to it [*Johnson*, 1965]. Since the wire is placed across a gaussian beam [*Goubau*, 1963, 1968], the current distribution in this wire will be of the following form:

$$I(z) = I_0 \exp[-(1/2)(z/z_0)^2] \qquad \text{(A8)}$$

where z_0 is the mode parameter of the gaussian beam. When the coordinate system shown in Figure 6 is used, the radiated field of a current element along the z axis is [*Harrington*, 1961]:

$$E_{(\theta)} = [j\omega\mu I_0 \exp(-jkr)\sin\theta/4\pi r] \cdot \int_{-l/2}^{l/2} \exp\left[-\frac{1}{2}\left(\frac{z}{z_0}\right)^2\right]\exp(jkz\cos\theta)\, dz \qquad \text{(A9)}$$

The current maximum I_0 may be determined from the increased beam attenuation caused by the wire scattering object.

Since the current distribution in the wire is gaussian and $l/2 > z_0$, the limits of integration may be extended to infinity with very little error. The radial component of the Poynting vector may then be written as:

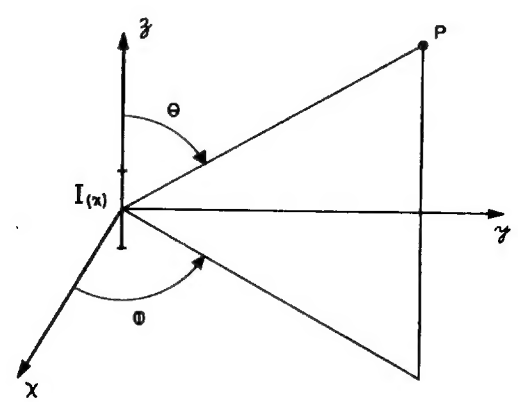

Fig. 6. Coordinate system.

$$S_r = \left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{I_0^2 k^2 z_0^2}{8\pi d_r^2} \sin^2\theta \exp(-k^2 z_0^2 \cos^2\theta) \tag{A10}$$

By equating the total scattered power to the measured power lost from the millimeter wave beam, one obtains

$$\frac{P L_{db}^S}{4.34} = \left(\frac{\mu}{\epsilon}\right)^{1/2} \frac{I_0^2 k^2 z_0^2}{4} \int_0^\pi \sin^3\theta \cdot \exp(-k^2 z_0^2 \cos^2\theta) d\theta \tag{A11}$$

where P is the beam power and L_{db}^S is the loss in db caused by the scattering wire. For the parameters employed, $kz_0 \gg 1$; therefore equation (A11) may be solved for I_0^2. Hence

$$I_0^2 = (4P L_{db}^S / 4.34\, kz_0)(\epsilon/\mu\pi)^{1/2} \tag{A12}$$

By substituting equation (A12) into equation (A10), one may now calculate the power received over an aperture. Thus

$$P_r = \frac{PL_{db}^S k z_0 A}{8.68\, \pi^{1/2} \pi d_r^2} \sin^2\theta \exp(-k^2 z_0^2 \cos^2\theta) \tag{A13}$$

By comparing (A13) with (A5), we find that

$$\sigma_0 = \frac{L_{db}^S k z_0}{2.17\, \pi^{1/2}} \sin^2\theta \exp(-k^2 z_0^2 \cos^2\theta) \tag{A14}$$

For the measurements performed in this experiment, the following parameters were used:

$\theta = \pi/2$
$k = 2\pi/\lambda = 7.33\ \text{cm}^{-1}$
$z_0 = 17.9$ cm
$t_1 = 10^{-5}$ sec
$D = 1.21$ cm

Equation (A14) then becomes

$$\sigma_0 = 34.11\, L_{db}^S$$

and the measured increase of loss due to the wire passing through the millimeter wave beam is 0.06 db. Using the relation

$$\alpha = L_{db}\, c/8.68\, d$$

the calibration equation then becomes in terms of measured parameters:

$$10 \log S = 3.12 + 10 \log (\mathcal{F}/D\mathcal{F}_0) + 10 \log (L_{db/km}/L_{0\,db/km}) + 3(L_{db/km} - L_{0\,db/km})$$

The total side-scatter coefficient can now be determined from measurements using the scatter properties of a known scattering object as a reference.

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